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Canopy damage by spring frost in European beech along the Apennines: effect of latitude, altitude and aspect

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ABSTRACT

Late spring frost plays a major role in the structure and function of forest ecosystems with potential consequences on species distribution at both local and regional scales. Paradoxically, in a warmer world the incidence and impact of frost is increasing because of earlier leaf unfolding and flowering as a response to warmer temperatures. In this regard, European Beech (*Fagus sylvatica* L.), a native tree species widely distributed in European forests, is considered particularly sensitive to changes in spring temperature regimes associated with climate change and thus especially subject to the risk of frost damage. Although several studies concerning *F. sylvatica* frost damage have been conducted in northern and central Europe, no extensive studies are available for the southern part of its range, i.e. central and southern Italy as well as Greece.

In this paper the effect of a late spring frost occurring at the end of April 2016 is extensively documented with high spatial detail all along the Apennine Chain through satellite image data. Three different remote-sensing greenness indexes, namely the normalized difference vegetation index (NDVI), enhanced vegetation index (EVI), and the greenness index (GI) derived from Landsat-8 satellite images acquired from May to July in the years 2014, 2015, and 2016 at a spatial resolution of 30 m, were used to gauge the spatial response of common beech forests to this late frost event with relation to latitude, altitude and slope exposure. Frost damage was evaluated as a difference (Δ) of NDVI, GI and EVI between the mean of years 2014 and 2015 (i.e. MRY, mean of reference years), and 2016 (i.e. FEY, frost reference year). The three satellite remote-sensing indexes were efficient at detecting leaf damage with detailed spatial resolution and proved consistent with one another.

The greatest damage occurred in the middle altitudinal range between 1500 and 1700 m a.s.l. with a decreasing trend toward both lower and higher elevations due to warmer temperatures below, and delayed phenology above. Exposure also influenced frost injury, with south-facing slopes of the mountain more damaged than the north. This difference was due to earlier spring leaf phenology of southern beech trees in response to a greater heat sum in the warm weeks preceding. Less damage in the northern Apennines is consistent with the spatial extent of minimum freezing temperatures. To sum up, frost damage is strongly related to site-specific conditions, i.e. on the one hand to minimum temperatures, and on the other to the phenological stage of the trees involving both altitude and exposure. Hence focusing on detailed sub-regional studies can be helpful for predicting future consequences of climate change on forests.

1. Introduction

Extreme climatic events play an important role in the structure and function of forest ecosystems (Smith, 2011; Bräuning et al., 2017). Spring frost, in particular, can limit plant growth and reproduction of individual trees, with potential consequences on species distribution at local and regional scales (Inouye, 2000). The impact of frost on trees is the result of the interaction between the timing of the event, i.e. full

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winter vs active growing season, the minimum temperature reached, and phenological plant status (reviews in Vitasse et al., 2014). Frosts that occur at the beginning of the growing season are usually more deleterious than freezing winter temperatures: the new emerging leaves and reproductive structures are more susceptible than woody tissues to frost, with intense damage occurring at temperatures of only −2 or −3 °C (Till, 1956; Sakai and Larcher, 1987; Mayer et al., 1988; Tranquillini and Plank, 1989), which are considered a threshold for frost hardiness of unfolding leaves.

The impact of intense frost damage on forest ecosystems can be long-lasting, extending over a period of years after the event (Inouye, 2000), with reduced plant growth in subsequent growing seasons (Dittmar et al., 2006). Frost damage is widely reported in North America (Gu et al., 2008; Augspurger, 2013), boreal ecosystems (e.g. Jönsson et al., 2004), and deciduous European forests (Menzel et al., 2015), with few studies involving the Mediterranean area (Garcia-Mozo et al., 2001). However, the frequency of spring frost damage in deciduous forests has increased since the mid-twentieth century as a consequence of climate change (Kramer et al., 2000; Augspurger, 2013). Paradoxically, in a warmer world the incidence and impact of frost are increasing (Cannell and Smith, 1986; Gu et al., 2008; Inouye, 2008; Augspurger, 2013). This occurs because plants grow more rapidly under warmer temperatures, resulting in earlier leaf unfolding and flowering that increase the likelihood of frost damage (Menzel, 2000). Indeed, current estimates on spring phenology suggested advancements by 2 d decade^{-1} over the last century (Parmesan and Yohe, 2003). The above trend is expected to increase in the near future, possibly leading to a severe impact on structure, function, and economic value of forests.

Temperate deciduous broadleaf tree species are especially susceptible because their frost tolerance is variable during ontogenesis and within the year (Menzel, 2000). Vulnerability to frost damage is greater for developing leaves. Phenological events of bud break and leaf unfolding are thus crucial factors in frost tolerance. In this regard, European beech (*Fagus sylvatica* L.), a widely distributed native tree species in European forests, is considered sensitive to changes in spring temperature regimes associated with climate change (Menzel et al., 2015) and particularly sensitive to spring frost damage due to the earlier onset of leaf unfolding and flowering (Packham et al., 2012), with frost especially harmful in the period ranging from mid-April to mid-May (Bascietto et al., 2018). Flowers, fruits and unfolding leaves of beech trees can be damaged from 2.0 °C to −2.5 °C, while temperatures below −4 °C can even kill the new shoots and reduce tree growth (Sakai and Larcher, 1987). Therefore, the native range of beech is confined by the intensity and frequency of late frost events, restricting the distribution at its eastern border (Bolte et al., 2007; Kramer et al., 2010), and determining its upper altitudinal limit in montane regions (Walter, 1986).

To date, studies concerning beech frost damage are available from northern and central Europe (Dittmar et al., 2006; Langvall, 2011; Menzel et al., 2015), where this species is present up to 1000 m a.s.l. However, no extensive study has been carried out in southern Europe, where beech reaches the treeline (Körner, 2012). The lack of knowledge concerning frost damage in beech at the southern limit of its geographical distribution greatly limits our ability to understand the ecological impacts of this extreme event at local and regional scales.

In mountain regions with complex terrain, topographical features such as elevation and aspect potentially affect frost impact. Aspect has a strong influence on air and soil temperature (Monteith and Unsworth, 2013), a factor that increases in intensity as slope increases (Wieser and Tausz, 2007). Consequently, in the Northern Hemisphere north-facing slopes are more shaded and colder than those facing south, which receive more solar radiation. We therefore expected frost impact to be greater on north-facing than on warm, south-facing slopes. We also expected increasing frost damage with the progressive decrease in temperature as altitude increased.

A late spring frost, occurring at the end of April 2016, damaged opening buds and young leaves, flowers and shoots, along many kilometers of montane areas. Although the event occurred throughout much of Italy and received considerable attention, it has so far been documented at local scale for just two restricted sectors of the central (Bascietto et al., 2018) and southern (Nolè et al., 2018) Apennines. The large scale of the event allowed us to study in detail, through satellite image data, its effect on forests throughout the entire Apennine Chain. Remote sensing techniques for detection of forest diseases and insect induced forest damage (Heller and Bega, 1973; Nelson, 1983; Rock et al., 1986) and for forest health monitoring (Tuominen et al., 2009) have been widely explored since the 1970s. First application of remote sensed images for detecting frost damage is reported by Jurgens (1997) in agricultural crops providing a timely and accurate approach to characterize spatially explicit information at landscape scales.

Herein we assess the spatial pattern of the damage to the beech canopy with relation to elevation and mountain aspect in order to corroborate the hypothesis that the impact of late spring frost is stronger in colder zones; i.e. that it increases with elevation (Walter, 1986; Čufar et al., 2012) and on north-facing slopes of mountains, as recently reported by Bascietto et al. (2018) for central Italy. To test this hypothesis throughout a large sector of montane beech forest, besides field observations, we used three different remote-sensing greenness indexes: the normalized difference vegetation index (NDVI, Rouse et al., 1974), enhanced vegetation index (EVI, Huete and Justice, 1999) and greenness index (GI, Gitelson et al., 2003) derived from Landsat-8 satellite images for the years 2014, 2015 and 2016 at a spatial resolution of 30 m so as to consider the entire Italian Apennines for change detection analysis to detect the frost damage which occurred in April 2016. Land Surface Temperatures (LST) extracted from the NASA data set MOD11A1 V06 (Wan et al., 2015) were also used to infer the geographical extent of the frost event.

2. Material and methods

2.1. Study area

The Apennines are a mountain chain nearly 900 km long, latitudinally oriented between 44°20′N and 39°40′N. The rocks are mainly limestone with few exceptions represented by arenaceous-pelitic flysch substrates and ophiolitic substrates (Bosellini, 2017). The climate is temperate-oceanic, with a relatively narrow annual temperature range and few extremes of temperature, being mitigated by proximity to the sea. Winters are wetter than summers, with most of the precipitation falling on the western Tyrrhenian side, with abundant snow cover from December to April at high elevation (> 1500 m a.s.l.). *F. sylvatica* represents the dominant tree species from 900 to 1800 m a.s.l. in the North (Pezzi et al., 2008) and to 2000 m a.s.l. in the South (Hofmann, 1991).

2.2. The frost event

On 25 and 26 April 2016, an advective frost caused by a horizontal delivery of cold-air masses from North-East Europe hit all of central and southern Italy, causing extraordinarily low nighttime temperatures that damaged beech canopies along many kilometers of montane areas (Supplementary Fig. S.1). Frost damage on *Fagus sylvatica* was observed on the ground at 6 sites in southern and central Italy, between April 2016 and August 2016; three of these sites were used for verification on the ground of the satellite data (Supplementary Fig. S.1).

To characterize the event with local detail, a daily meteorological instrumental dataset with minimum and maximum air temperatures in March–April 2016 was constructed with data measured 2 m above ground level from three weather stations very close to forested areas in the southern (2010–2016, Campotenese, 39.87 N 16.06 E, 973 m a.s.l.), central (2007–2016, Passo Godi, 41.85 N 13.93 E, 1560 m a.s.l.) and northern Apennines (2002–2016 period, Ligonchio, 44.18 N 10. 21 E, 940 m. a.s.l.). Averages were calculated excluding 2016. In order to

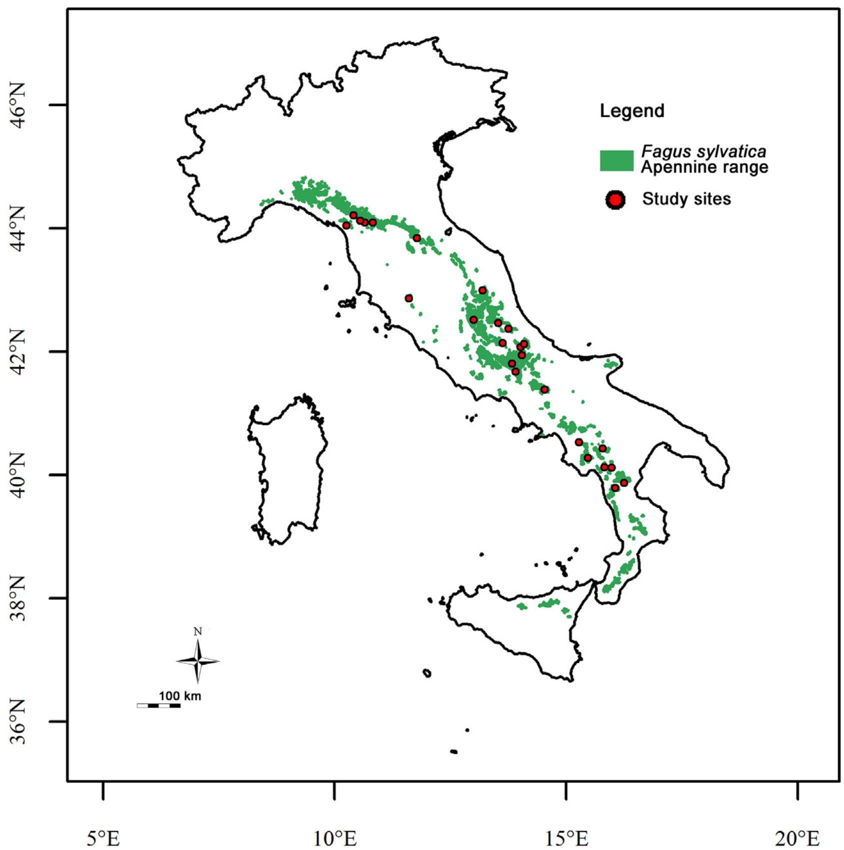

Fig. 1. Distribution of the 24 study sites along the Apennines.

further evaluate the geographical extent of the climatic event, we investigated the spatial distribution of Land Surface Temperatures (LST) extracted from MOD11A1 V06 (Wan et al., 2015).

2.3. Satellite remote sensing and climatic data collection

In our analysis, 24 sites were selected to represent the whole Apennine range (Fig. 1). Within the distribution range of *F. sylvatica* extracted from the Corine Land Cover (CLC) Level IV 2012 (available at http://wms.pcn.minambiente.it/ogc?map=/ms_ogc/wfs/Corine_Land_Cover2012.map), we selected all sites where mountains peaks reach an elevation of at least 1500 m a.s.l. with long uniform mountain slopes, i.e. without sharp drops in height; peaks were mapped by hands in Google Earth Pro™ (Google, Inc. Mountain View, CA, USA) images dating 2004–2011. A further selection was made on the basis of satellite image quality, excluding those sites where images had a cloud cover of > 20%.

Overall, 247 sampling points were selected at approximately 100 m altitudinal intervals along North- and South-exposed transects across the altitudinal distribution of the species in each site (Supplementary Table 1). In order to provide high quality data representative of the *F. sylvatica* forest type, sampling points were selected by excluding areas with rocks, grassland, buildings or roads. Each sampling point covered an area of 7875 m^2.

Remotely sensed data at 30 m resolution covering the entire study area included a total of 30 images of the Landsat-8 OLI. For this study, atmospheric corrected images were used. We downloaded Landsat Surface Reflectance Level-2 Science Data Products, 30 images in all, each one with a cloud cover of < 20%, for the 247 sampling points from the on-line archive of the USGS Earth Resources Observation and Science (EROS) Center Science Processing Architecture (ESPA) On Demand Interface. Landsat-8 Surface Reflectance data are generated from the Landsat Surface Reflectance Code (LaSRC). A detailed description of the algorithm and the validation of Landsat-8 OLI is presented in Vermote et al. (2016). Satellite images in each sampling point were selected in the time interval close after the frost event (April 25–26) between May 6 and July 3 in the years 2014 and 2015, considered as reference years as they were lacking in extreme events, and 2016, which is the year of the frost event (Supplementary Table 1, Fig. 2). Within this range of time, cloud cover < 20% conditioned the images acquisition date.

All acquired images for each selected site and data were extracted for the sampling points. The selected sampling points were additionally visually inspected to avoid the influence of the pixels that included clouds and snow.

Blue, green, red and NIR bands were automatically extracted from satellite images in each sampling point in the time interval close after the frost event (April 25–26) between May 6 and July 3 in the years 2014 and 2015, considered as reference years as they were lacking in extreme events, and 2016, which is the year of the frost event (Supplementary Table 1, Fig. 2).

2.4. Data analysis and statistics

Normalized difference vegetation index (NDVI) (Rouse et al., 1974), greenness index (GI) (Gitelson et al., 2003) and enhanced vegetation index (EVI) (Huete and Justice, 1999) were computed for each chosen sampling point as follows:

$$\mathrm{NDVI} = \frac{(\mathrm{NIR} - \mathrm{Red})}{(\mathrm{NIR} + \mathrm{Red})}$$

$$\mathrm{GI} = \frac{\mathrm{NIR}}{\mathrm{Green}}$$

$$\mathrm{EVI} = 2.5\,\frac{(\mathrm{NIR} - \mathrm{Red})}{(\mathrm{NIR} + 6\cdot\mathrm{Red} - 7.5\cdot\mathrm{Blue} + 1)}$$

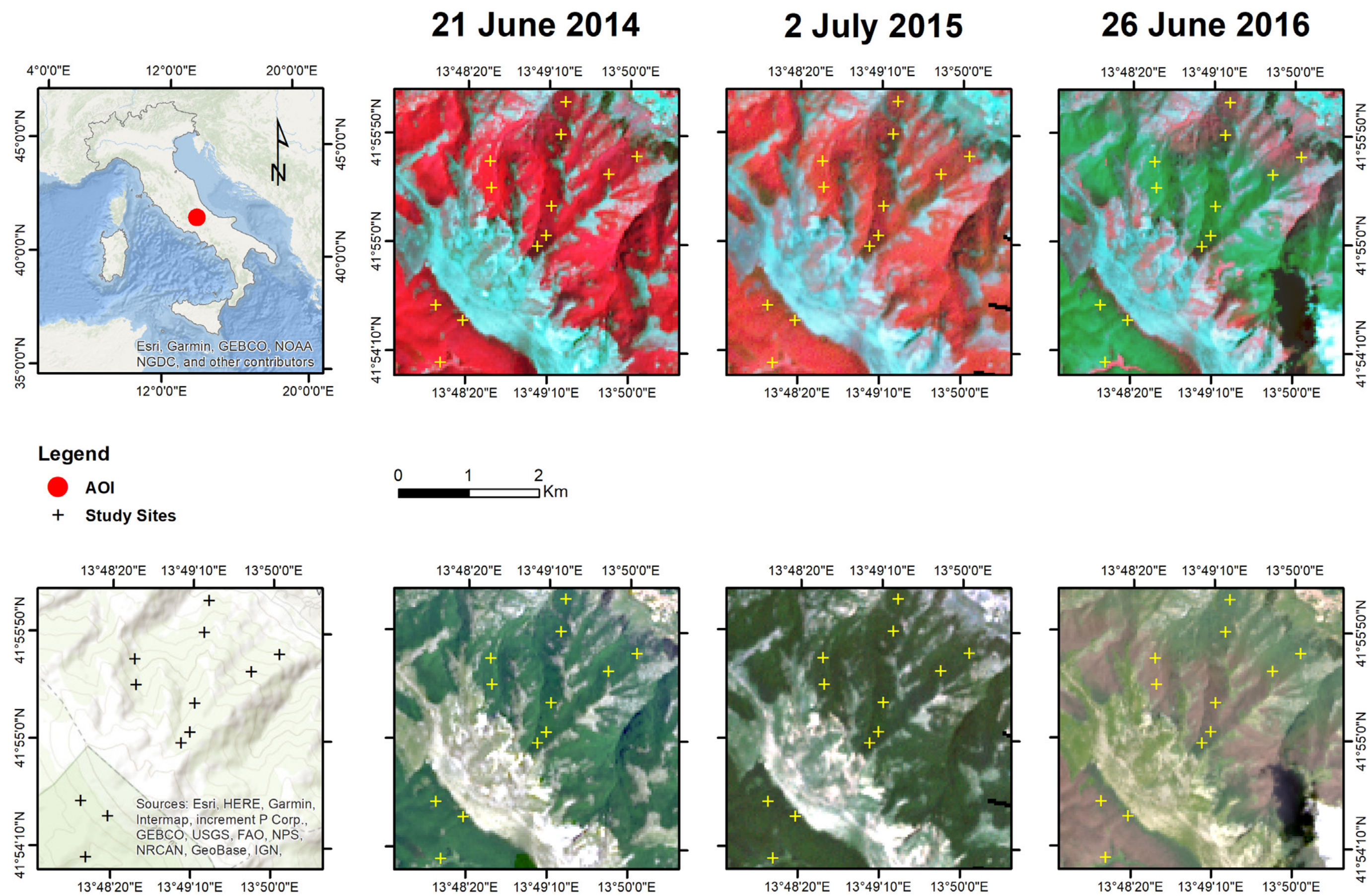

Fig. 2. Example of Landsat-8 satellite acquisitions for Mt. Argatone (Central Apennines): time series of Landsat-8 color infrared with vegetation as red (RGB = Band 5, Band 4, Band 3) in the upper panels, and natural color with vegetation as green (RGB = Band 4, Band 3, Band 2) in the lower panels. Crosses represent the sampling points selected at approximately 100 m altitudinal intervals in the study site (Supplementary Table 1). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

where blue, green, red and NIR indicate the surface reflectance acquired in the visible (blue, green and red) and near-infrared regions of the electromagnetic spectrum.

To test among-year differences in NDVI, GI and EVI a post hoc SNK test was used after one-way analysis of variance (ANOVA). We used a significance level of 1% and log transformed the data to meet the assumption of a statistical test. Frost damage was then evaluated as a difference (Δ) of NDVI, GI and EVI between the mean of years 2014 and 2015 (i.e. MRY, mean of reference years), and year 2016 (i.e. FEY, frost reference year).

Linear regressions were performed using the '*lm*' function in R version 3.3.0 (R Core Team, 2017) to describe the relationship of the Δ vegetation indexes respectively with latitude, altitude and aspect. Altitude and latitude were included each one in a regression model as independent variables, while, aspect was included in both the regression models as a dummy variable. Among all possible model combinations in terms of form (i.e., first-order and second-order) and variable interaction (i.e., first-order with and without interaction term), the best models were selected according to the lowest Akaike information criterion (AIC) score.

3. Results

3.1. Weather conditions

In the three weeks preceding the frost event, between April 1 and 24, the maximum temperature of the Nighttime LST derived from MODIS TERRA was 14.3 °C both in the southern Apennines at 1400 m a.s.l. and in the central Apennines between 1100 and 1200 m a.s.l. In the same period, the lowest temperature, calculated as the average of all the acquisitions between DoY 92–116 at 10:30 pm of the Nighttime LST from MODIS TERRA, was 1.8 °C at 1800 m a.s.l. in the central Apennines, while the highest average from the same acquisitions was 8.0 °C, calculated at Gran Sasso, between 1100 and 1200 m a.s.l. (Fig. 3; Supplementary Table 2). The lowest nighttime land surface temperature derived from MODIS TERRA acquired on 25 April 10:30 pm was −9.2 °C reached at 1800 m a.s.l. in the central Apennines, while at the same elevation the temperature recorded in the southern Apennines was −3.9 °C. In the northern Apennines the lowest temperature was −1.37 °C, recorded at 1600 m a.s.l. (Fig. 3; Supplementary Table 2).

At the three monitoring stations, daily minimum and maximum air temperatures in March–April 2016 were consistently higher than their respective long-term average trends especially in the central and southern Apennines (Fig. 4). The warmest day was recorded on 5 March 2015 (95 DoY) in the northern and central Apennines with a respective maximum temperature of 19.9 °C and 17 °C, and on 18 April 2016 (108 DoY) in the southern Apennines with an air temperature of 23.9 °C (Fig. 4).

The extreme climatic event was recorded at all three monitoring stations (Fig. 4). A sharp fall in nighttime temperature occurred between 24 and 25 April in the North and between 25 and 26 April in central and southern Italy. Both maximum and minimum daily temperatures were below the long-term mean; the lowest minimum temperatures were recorded in central and southern Italy, reaching respectively −7.6 °C and −2.9 °C while in the North the minimum was

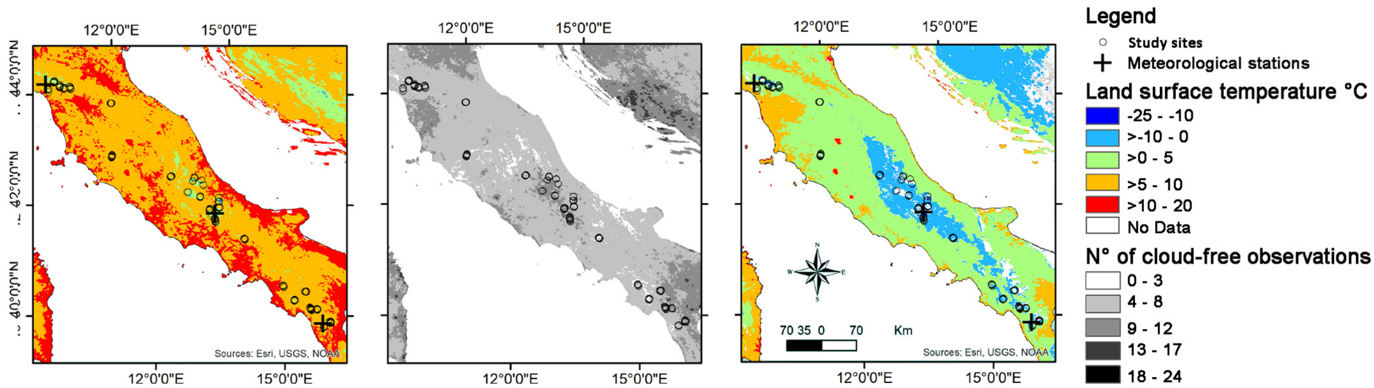

Fig. 3. Average nighttime land surface temperature derived from MODIS TERRA acquired from 1 to 24 April 2016 (first panel) based on the number of cloud-free observations (second panel); nighttime land surface temperature (°C) derived from MODIS TERRA acquired on 25 April 10:30 pm local time (third panel).

−1 °C.

3.2. *Beech frost damage*

Large variations in the indexes (NDVI, GI, EVI) were evident between the years in question, with the mean values significantly lower for 2016 compared with 2014, 2015 (Fig. 5, Supplementary Table 3 and Supplementary Table 4).

With regard to Δ data plotted against latitude, the three indexes are consistent with one another, showing mostly positive Δ data (Fig. 6, left panels; Supplementary Table 5). Overall, regressions against either latitude or altitude showed the lowest explained variance for ΔGI (6%

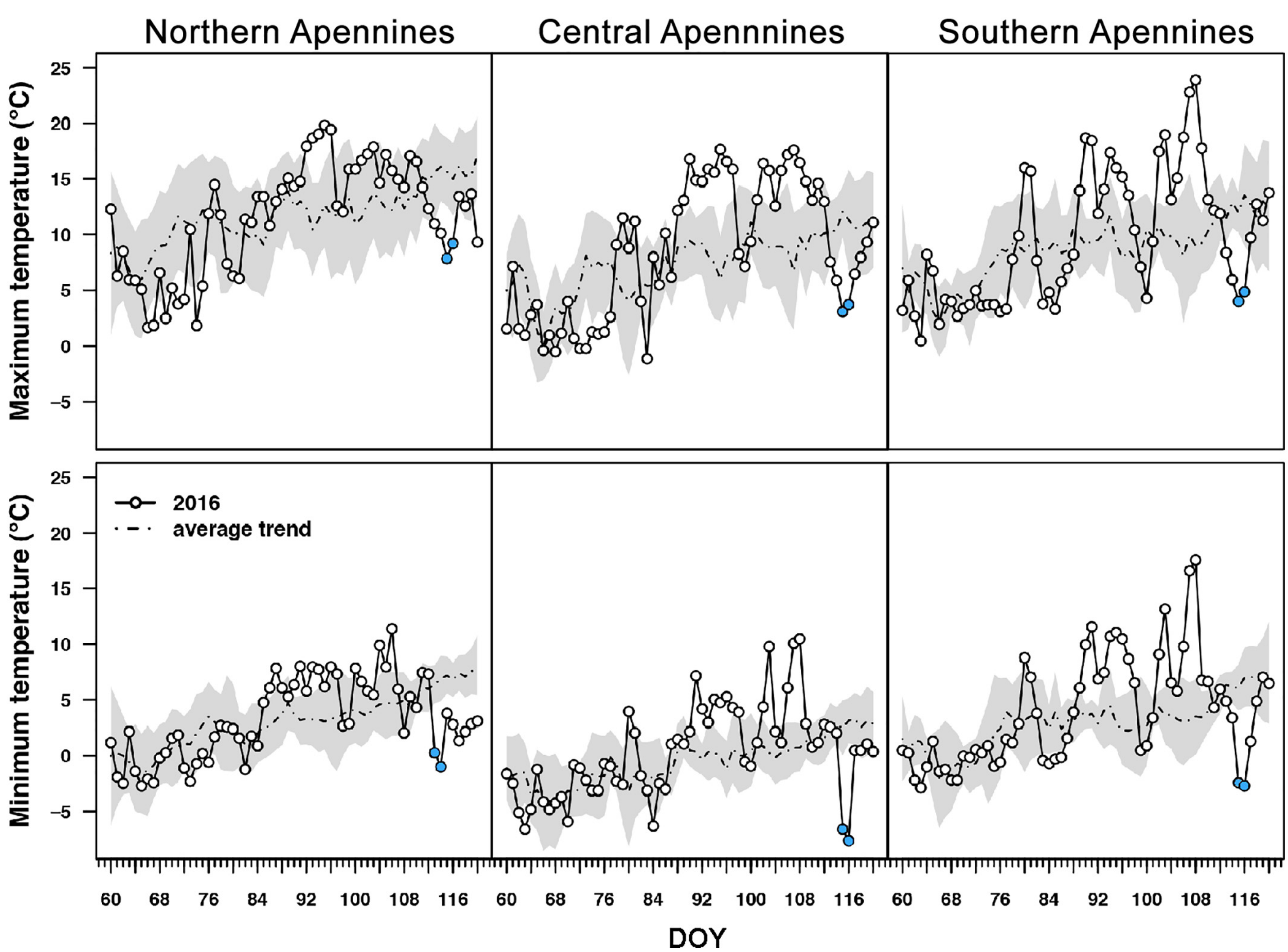

Fig. 4. Maximum and minimum daily temperature registered in March–April 2016 (solid line) and daily average trend calculated excluding FEY (dashed line); the shaded polygon represents the first standard deviation. Blue-filled circles represent days when frost occurred. Data came from Ligonchio (northern Apennines, 44.18 N 10.21 E, 940 m. a.s.l. Data time series 2010–2016), Passo Godi (central Apennines, 41.85 N 13.93 E, 1560 m a.s.l. Data time series 2002–2016) and Campotenese (southern Apennines, 39.87 N 16.06 E, 973 m a.s.l. Data time series 2007–2016). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

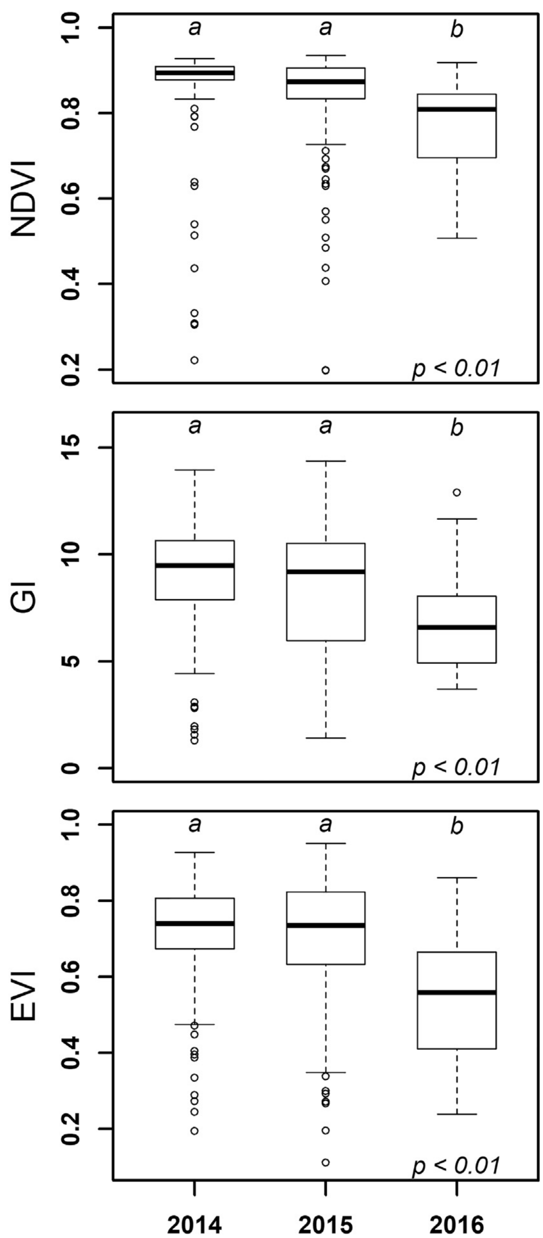

Fig. 5. Box plot of the calculated indexes for the years 2014, 2015 and 2016. Different letters above the boxes indicate significant different means at p < 0.01 (ANOVA with pairwise post-hoc test, Supplementary Table 3 and Supplementary Table 4).

and 8%, respectively) compared to ΔNDVI and ΔEVI. To be more specific, the regression line shows a slightly negative slope from southern to northern latitudes and the difference in the intercepts suggests that frost damage was higher in the southerly aspect. The best fit of Δ data plotted against altitude (Fig. 6, right panels) was obtained with a second degree polynomial function. The convex shapes of the curves evidenced higher Δ data between 1500 and 1700 m a.s.l. with slight higher intercepts for the southern aspects. In Fig. 7, pictures of the brown canopy bands due to the late spring frost event taken in May–-June 2016 at three study sites (Mts. Majella, Mts. Sibillini and Mt. Pollino) are shown beside their respective ΔNDVI, ΔGI and ΔEVI indexes plotted against elevation.

4. Discussion

Late frost damage is a well-known worldwide risk for a number of tree species both in temperate and boreal ecosystems (Jönsson et al., 2004; Hänninen, 2006; Hufkens et al., 2012; Morin and Chuine, 2014). In central Europe, late frost events affecting beech occurring until mid-May have been well documented (Dittmar and Elling, 2006; Ningre and Colin, 2007; Kreyling et al., 2012; Menzel et al., 2015) while little is known about frost risk at southern latitudes (Bascietto et al., 2018).

Our study documents for the first time, with high spatial resolution, both the altitudinal and latitudinal pattern of the canopy frost damage along a large area of montane beech forest in the Mediterranean area. Here, all along the Apennine chain, strips of beech forest turned dramatically brown several kilometers wide, showing the damage on opening buds, young leaves and shoots.

NDVI and EVI have been widely used as an important vegetation monitoring tool both as a diagnostic indicator of phenological development and health (Goward et al., 1991; Pettorelli et al., 2005; Pettorelli, 2013), although the EVI is more sensitive to variability in densely vegetated surfaces than the NDVI (Huete and Justice, 1999). Conversely, the Greenness Index (GI) (Gitelson et al., 2003) has been less exploited as a vegetation index, but is described as the most sensitive to phenological development (Gitelson et al., 2005) due to its greater sensitivity to chlorophyll than both NDVI and EVI (Gitelson, 2004). In this study the EVI index was calculated by using Landsat-8 data, unlike Bascietto et al. (2018) who used MOD13Q1 in the central Apennines. Indeed, the spatial resolution of Landsat-8 is more suitable than MODIS to detect damaged areas of limited extent when considering the entire Apennines. Calculations based on the three satellite remote sensing indexes were in agreement, the mean of 2016 values being significantly lower than the control years.

The difference between MRY and FEY was mostly positive for all the selected indexes, suggesting that all three indexes were efficient at detecting canopy frost damage with detailed spatial resolution.

The relative severity of the damage (different damage levels) determined in situ by ΔNDVI, ΔGI and ΔEVI provided valuable information for understanding the spatial response of common beech forests to this late frost event with relation to latitude, altitude and slope exposure. With relation to latitude, a trend of reduced frost severity is observed from the southern to northern Apennines. This seems consistent with the spatial extent of the frost event which only marginally affected the northern Apennines (Figs. 4 and 5; Supplementary Table 2).

Along the Apennines, the greatest damage occurred in the middle altitudinal range between 1500 and 1700 m a.s.l. with a decreasing trend toward both lower and higher elevations. This pattern can be easily related on the one hand to minimum temperature trends against elevation, and on the other to the phenological stage of the trees. Indeed, along the altitudinal gradient, at the lower belts, below 1200 m a.s.l., temperatures remained warmer, preventing canopy damage. Instead, since leaf unfolding trends are closely related to altitude (Dittmar and Elling, 2006; Čufar et al., 2012; Vitasse et al., 2014), above 1700 m a.s.l. trees were still dormant. In the first week of May 2016 in the Pollino massif (southern Italy), at 1900–2000 m a.s.l. new leaves had not yet unfolded, while between 1500 and 1700, 90% of the leaflets were 50% expanded (G. Bonanomi, personal observations). This evidence, calls into question that spring frost damage can be a factor limiting *F. sylvatyca* recruitment and survival at the treeline (Bonanomi et al., 2018). Slope exposure also influenced frost injury but, contrary to our expectations, the southern slopes of the mountain experienced more damage than those on the north. To note, that our outcomes also disagree with Bascietto et al. (2018), which, presumably for the lower spatial resolution of their data (MOD13Q1, 250 m), inferred, for a restricted sector of Central Apennine, a negative, although weak, influence of the south and west facing on the probability of late frost damage.

Also in the case of the slope exposure, the different timing of spring leaf phenology seems to be the main factor: trees on the northern slopes may have been better preserved by damage due to the slight delay in

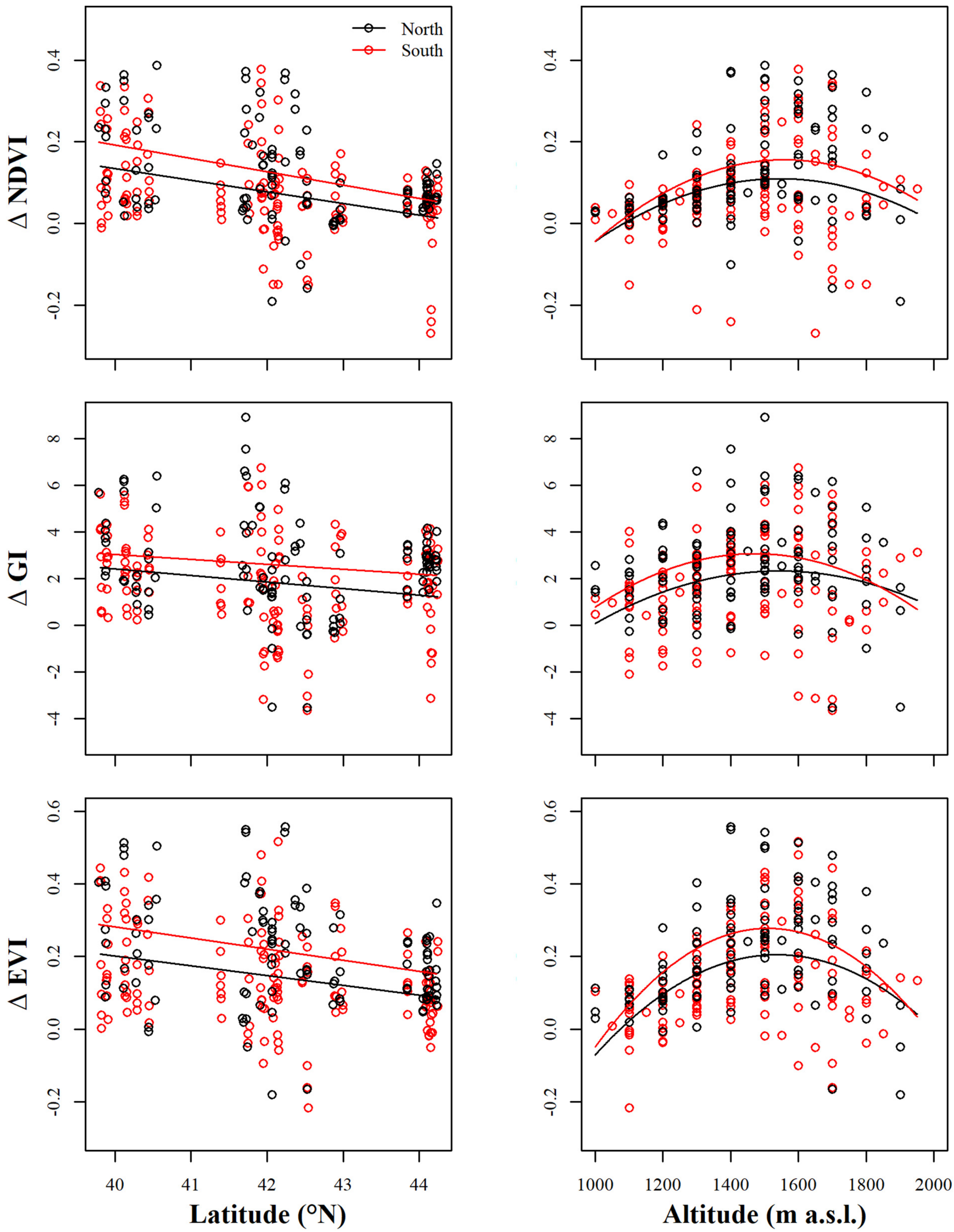

Fig. 6. Relationship between ΔNDVI, ΔGI and ΔEVI and latitude (left panels) and altitude (right panels). Open circles for northern (black circles) and southern (red circles) aspects. Solid lines represent linear regression in the left panels, and a second-degree polynomial regression in the right panels. Black and red represent northern and southern aspects, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the leaf unfolding phase *vis-à-vis* the southern slopes due to the lower heat sum in the warm weeks preceding the event in question (Supplementary Table 2).

Our results show that damage severity depends on the interaction between freezing temperatures and phenological stage. Indeed, while winter buds have a relatively high frost tolerance, during bud-break and leaf unfolding the tolerance to frost is very low (Dittmar et al., 2006; Kramer, 1994), increasing again after hardening of the leaves (Kreyling et al., 2012). Sakai and Larcher (1987) report that actively expanding leaves of beech are highly vulnerable to frost and are susceptible to

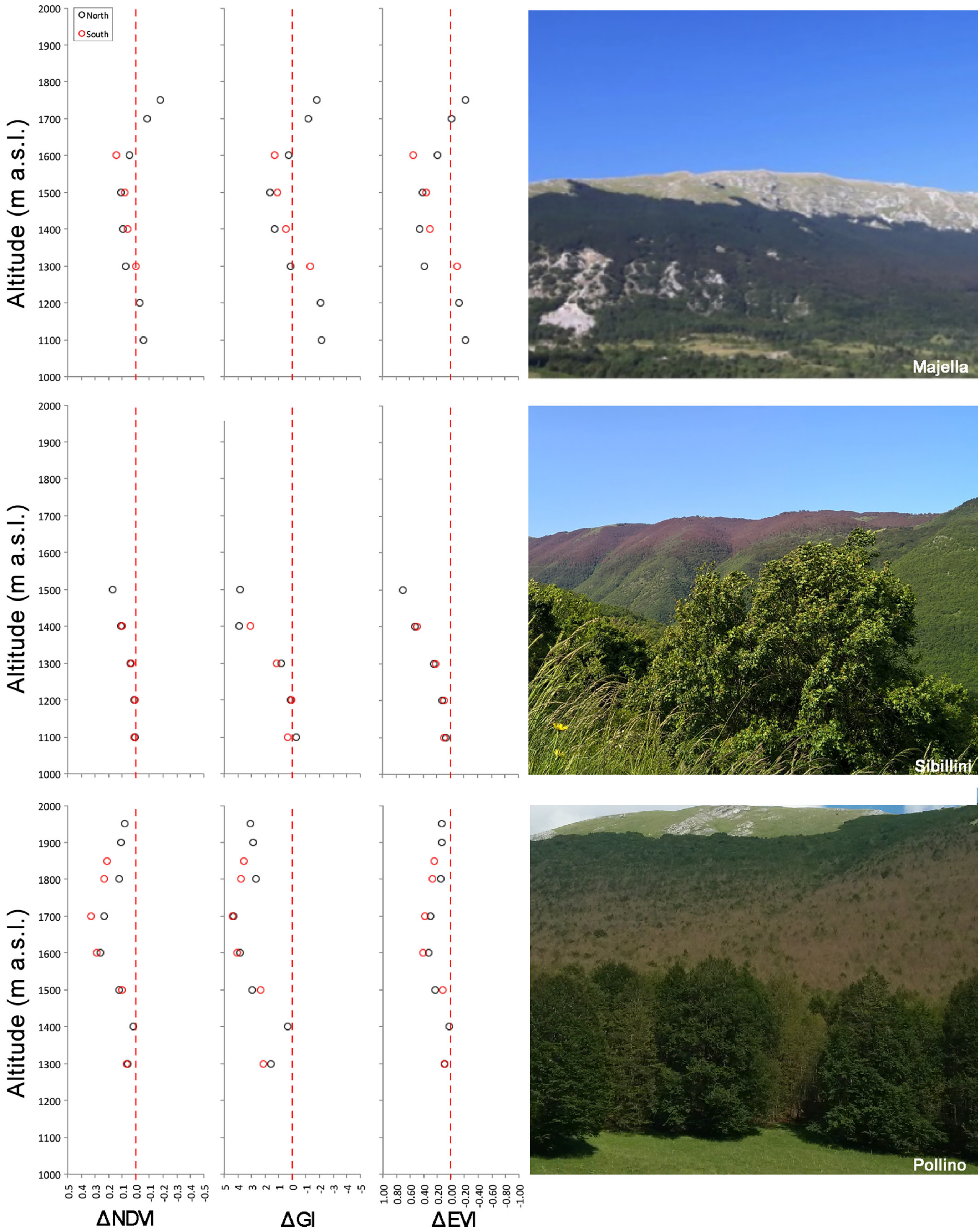

Fig. 7. ΔNDVI ΔGI and ΔEVI plotted against elevation shown besides their respective overview pictures, taken on the ground between May and June 2016 after the late frost event. From top to the bottom: Majella Mts, Sibillini Mts and Pollino Mt.

−2–2.5 °C frost. Similarly, Dittmar et al. (2006) report that temperatures under −3 °C can affect the radial growth of beech, in line with Tranquillini and Plank (1989), Mayer et al. (1988) and Till (1956) who suggest −3 °C as the threshold value for frost hardiness of unfolding leaves. In this perspective, the timing of leaf flushing in relation to minimum temperature is the principal determinant of the late spring frost damage.

Along the Apennines, due to the very warm spell from the end of March 2016 (Fig. 3; Supplementary Table 2), beech trees anticipated their flushing. For example, in the southern Apennines (latitude 39°–40° N), beeches showed unfolded leaves from 10 April at 1200–1300 m a.s.l. (GB, personal observation). This early flushing coupled with the severe frost event resulted in exceptional damage both in terms of geographical extent and local intensity.

The effect of global climate change on spring phenology of trees has been widely studied and assessment of the likelihood of frost damage related to the timing of bud burst and the subsequent risk of frost damage on trees is of major interest in a context of climate change (Murray et al., 1989; Hänninen, 1991; Kramer, 1994; Augspurger, 2013). The end of winter dormancy and start of leaf unfolding in late-successional tree species such as beech are generally known to depend mainly on photoperiod (Murray et al., 1989; Heide, 1993; Caffarra and Donnelly, 2011) while in early-successional species bud phenology is more dependent on temperature (Basler and Körner, 2012). Although, among comparable deciduous trees species, the temperature response of beech is the smallest (Menzel et al., 2001), the literature has extensively documented increased risk of frost damage due to a shift in leaf phenology following warmer spring temperatures (Kramer, 1995; Von Wuehlish et al., 1995; Čufar et al., 2012; Menzel, 2000; Augspurger, 2013).

Overall increases in mean temperatures and the occurrence of erratic severe weather patterns, with heavy spring frosts, are expected to increase, at least in this century (Gu et al., 2008; Kodra et al., 2011).

5. Conclusions

High resolution satellite data were able to show on a large sector of Apennine montane beech forest that frost damage is strongly related to site-specific conditions, i.e. on the one hand to minimum temperatures, and on the other to the phenological stage of the trees, involving altitude, aspect and seasonal trend.

Therefore, for the above reasons, focusing on detailed sub-regional studies can be helpful to predict future consequences of climate change on forests. Given the impact and increasing frequency of such extreme events on forests, especially in the light of the predicted climate change, it becomes increasingly essential to make a major effort to investigate forest damage with spatial detailed studies in relation to both the phenological response to the warming climate and to the frequency, magnitude and timing of severe frosts.

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